

A Review of Ferroalloy Tapping Models



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Tapping is an important furnace operation in the ferroalloy industry and poses a number of complex and coupled challenges of both practical and economical importance. Owing to the hazardous high-temperature conditions surrounding the tap hole, the application of various modeling techniques allows for development and acquisition of both scientific and engineering knowledge of the process through physical or numerical proxies. In this review, earlier work on modeling of ferroalloy tapping is summarized and main principles of the tapping process and multiphase interaction of slag and metal are discussed and summarized. The main focus is on drainage of slag and alloys, but some attention will also be given to metal loss, metal overflow and health, safety and environment. Our review shows that although considerable progress has been made in computational capability over the last decades, However, it is clear that research and development in the field of ferroalloy furnace tapping remains at a relatively nascent stage. The most progress up to date has happened in the area of so called reduced-order models. Such models are robust and simple, and may be easily fitted to process data from a particular operation in order to develop tailored solutions. Such models are more easily combined with software and instruments, ultimately enabling improved automation, process control and ultimately improved tapping consistency.

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I. INTRODUCTION

FERROALLOYS refer to different alloys of iron with high content of other elements (*i.e.* Mn, Si, Cr, Ti), used in the production of steels and alloys to improve properties such as strength, ductility, and fatigue or corrosion resistance. The ferroalloy production volume is greatly dependent on steel production, which means that the production of ferroalloys changes alongside steel production. In the period from 1990 to 2010, the total world steel production has increased from 770 to 1400 million tones and, similarly, ferroalloy production has risen from 20 to 45 million tones.^[1]

Ferroalloys are mostly produced in submerged arc furnaces (SAF) during carbothermic reduction of oxide raw materials at high temperatures, where the main smelting products are molten metal and slag. A ferroalloy producing furnace is shown in Figure 1 with a schematic of the entire production process as presented in Figure 2.

The processes taking place in the SAF are typically a combination of solid-gas, solid-solid, solid-liquid and liquid-liquid reactions, with an overall reaction “ $MO + C \rightarrow M + CO$ ”, *i.e.* producing metal from the corresponding metal oxide, which often can be in multiple oxidation states. In addition to metal, slag is also produced as a by-product in the SAF. The slag in ferroalloy production consists of a mixture of different oxides (*e.g.* MnO, CaO, MgO, SiO₂, Al₂O₃). The overall process is endothermic, meaning that heat must be supplied to the furnace. The heat required for endothermic reactions, heating the coke bed and to compensate for heat losses is supplied by electrodes, which are submerged in the coke bed. Heating in the SAF takes place by the flow of electricity between the electrodes, through the coke bed and slag to molten metal.^[2]

The removal of the molten material from a furnace is performed through a process called tapping. Tapping is the transitional process step where the alloys are transferred from a furnace in which they are produced into a ladle or a set of ladles where further processing may take place. The furnace tapping can be illustrated

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schematically as shown in Figure 3. In the ferroalloy production industry, tap-holes are made from carbon, silicon carbide or other refractory materials.^[3-5] Some furnaces operate with a continuous tapping scheme, but most of them are tapped every 2 to 4 hours.^[5,6] The tapping operation usually lasts 10-15 min, depending on the size of the furnace and ladles, and consist of several stages:

- (A) Tap-hole opening by an automatic or semi-automatic tap-hole drill. Besides that, oxygen lancing can be carried out in case of viscous flow or clogging of the tap-hole. This auxiliary operation supplies oxygen as a source of heat to the tap-hole, thereby melting and penetrating the materials clogging the tap-hole.^[7] Excessive lancing is highly undesirable and must be used only when drilling fails because it results in difficulties during next tapping and extensive wear of the tap-hole refractory. This stage often involves manual work of operators near the tap-hole area and therefore is considered a most dangerous operation.^[8]
- (B) Filling of metal and slag ladles. At this stage, the tapping flow rate is determined by physico-chemical properties of the molten material and the geometry of the furnace and the tap-hole.^[9] In addition, the hydrostatic equilibrium plays an important role because it acts as the driving mechanism of tapping. It can be characterized as the balance between three forces: downward force due to the pressure from fluid above in the furnace (pressure), weight of fluid contained in volume (gravity), and upward force

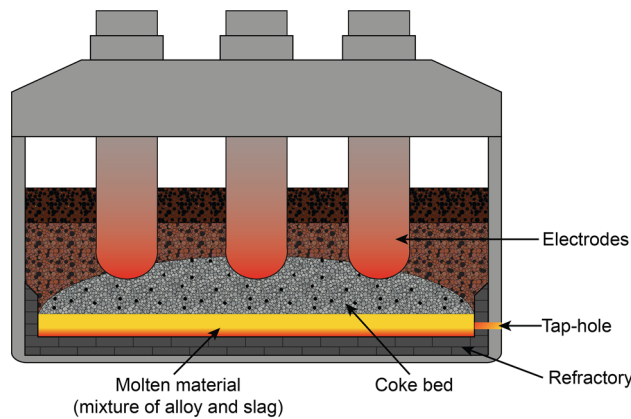


Fig. 1—Schematic of a submerged arc furnace for production of ferroalloys.

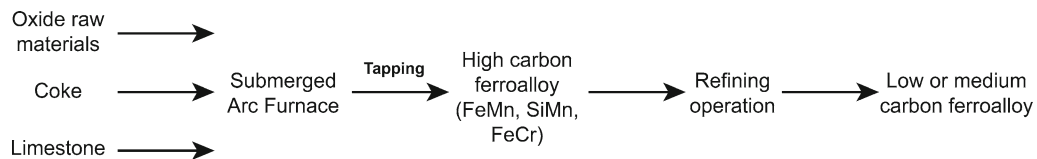


Fig. 2—Simplified ferroalloy production flowsheet.

due to pressure from fluid below, physical barriers and solid particles (resistance). In the metal ladle, the slag and alloy separate from each other due to density differences, and as soon as it is filled, liquid slag overflows to the slag ladle, often involving a significant amount of alloy droplets.^[4]

- (C) After the metal ladle is filled with molten alloy, the tap-hole is plugged by a mudgun loaded with a tap-hole clay (mixture of Al_2O_3 , SiO_2 and C).^[2,10]
- (D) Post-tap-hole processing: slag remaining on top in the metal ladle has to be removed by manual tilting the ladle and skimming off the slag with a mechanical rake.^[11] This stage results in additional losses of ferroalloy with slag.

There are several alternative methods for tapping of products from the SAF; combined metal and slag tapping, dedicated metal-slag tapping and slag-only tapping.^[4] Each of these methods have different operational difficulties, which may result in non-stable furnace operation and hazardous environmental conditions. This includes, for example, challenges with tap-hole opening due to viscous flow or a significant amount of solid coke particles in the molten flow.

Another important aspect of the furnace tapping is the entrainment of ferroalloy droplets by slag.^[13] The interactions between metal and slag are governed by interfacial phenomena, which are characterized by the interfacial tension.^[14-16] Surface-active elements (*e.g.* oxygen, sulphur) in the ferroalloy-slag system result in intensive reactions at the alloy-slag interface,^[17] which

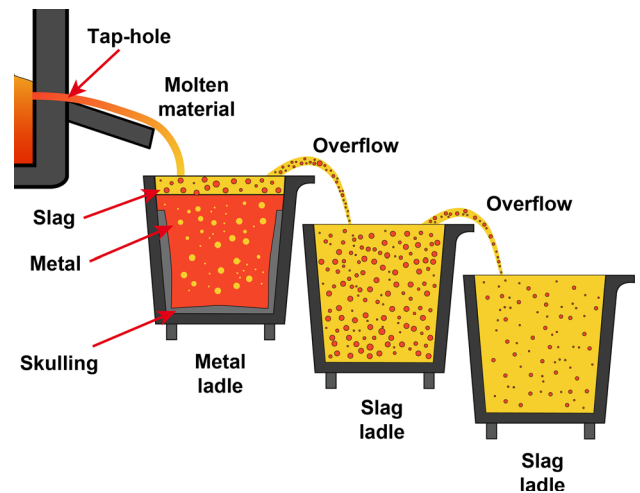


Fig. 3—Tapping of SAF.^[12]

contribute to a dynamic change of the interfacial tension between alloy and slag until thermodynamic equilibrium is reached.^[18,19] This affects metal loss to the slag phase during cascade tapping—see Figure 3.

Different aspects related to tapping of SAFs can be investigated using mathematical models and computational fluid dynamics (CFD).^[9,20,21] Such approaches can provide great insight to the operation, and the knowledge gained from properly constructed studies with such tools can ultimately improve the consistency of tapping.

In this review, earlier work on modeling of ferroalloy tapping is summarized and main principles of the tapping process and multiphase interaction of slag and metal are discussed. Moreover, advantages and disadvantages of various approaches are given, followed by an assessment of their general applicability. The main focus is on drainage of slag and alloys, but some attention will also be given to metal loss, metal overflow and issues related to health, safety and environment (HSE). Although the focus of the current work is modeling of ferroalloy tapping SAFs, selected studies on blast furnace tapping models are also discussed, since the drainage mechanisms are very similar. However, this is not a full review of blast furnace tapping models.

II. PHYSICAL AND NUMERICAL MODELS

Different approaches to modeling of the tapping process in ferroalloy production have been conducted; categorized as physical or mathematical modeling. We will mainly focus on mathematical modeling since the work on physical modeling is very scarce. An experimental setup with a physical representation of the process or phenomena to be studied defines a physical model. For ferroalloy tapping this should in principle involve a drainage experiment with at least one liquid phase and a particle bed. Although several physical drainage experiments have been reported in the literature, few have considered the particle bed.

Nouchi *et al.*^[22] performed a drainage experiment resembling a scaled down version of a blast furnace with two liquids (paraffin and fluoride) in a particle bed of plastic beads, highlighting that liquid drainage velocities are dominated by the permeability in front of tap-hole.

A similar study was performed by Vango *et al.*,^[23] considering a water tank experiment with spherical wood particles. They designed the experiment such that the particle bed could be sitting or floating. The results showed that a floating particle bed adds weight and thus driving pressure, resulting in faster drainage.

Mathematical models can relate to many aspects of the process including thermochemical properties, material erosion and wear and more. In this paper, we focus on mathematical models for the drainage of slag and metal from the furnace. In addition, it is necessary to differentiate between reduced order modeling and CFD. In principle, CFD can be defined to include all mathematical models describing flow, but here we limit CFD to mathematical models solving the full 3D (or 2D) set of conservation equations for mass and momentum by a

numerical algorithm. With reduced order modeling we refer to a modeling scheme where the model complexity is reduced through various assumptions allowing for reduction in solution time and/or data storage. An overview of published work is discussed in the following sections.

A. Reduced Order Modeling

In modeling the draining flow from a furnace, Bernoulli's equation provides a reasonable representation of the flow between two points in a geometry. The equation is based on conservation of mechanical energy along a flow line. Models based on this principle are used in textbooks in Fluid Dynamics with drainage as an example, and all known reduced order models for furnace tapping apply Bernoulli's equation to our best knowledge.

The tapping rate for a tank with a liquid can be estimated by Bernoulli's equation (see *e.g.* Guthrie^[24]):

$$\dot{m} = \frac{\rho C_D \pi d^2}{4} \sqrt{2gH} \quad [1]$$

where d is the diameter of the tap-hole, ρ is the density of liquid, C_D is the drag coefficient, g is the acceleration due to gravity. Here, the hydrostatic head H provides a pressure which is the driving force of tapping. In a furnace, a viscous resistance will be present due to the particle bed of carbon material and ore. The driving force will also be affected by the furnace pressure. The tapping of a submerged arc furnace is therefore more complex than tapping of water through a hole in a tank. Mitsui *et al.*^[25] modified the above expression by accounting for a furnace pressure (crater pressure) and by applying the idealized pressure drop through a channel for the pressure drop through the tap-hole:

$$\dot{m} = \frac{\rho \pi d^2}{4} \sqrt{\frac{2gH + P/\rho}{1 + \lambda l/d}} \quad [2]$$

where λ is the wall friction constant of the tap-hole and l is the length of the tap-hole. They did not account for the pressure drop due to the particle bed. The particle bed pressure drop was included in the reduced order model of Nouchi *et al.*^[22] and Iida *et al.*^[26] for iron and slag tapping from a blast furnace. They also accounted for two liquids (metal and slag) with a mixture model which in principle is a single-phase model, but material properties are derived by an average of the two liquids' properties. Shao and Saxen^[27] derived a drainage model for blast furnaces treating the two liquids as segregated immiscible phases. This allowed for separated estimates of metal and slag tapping rates, whereas earlier models only provided a total tapping rate.

All of the above-mentioned work on reduced order modeling was applied towards blast furnaces and steel production. Muller *et al.*^[9] applied the modeling concept of Iida *et al.*^[26] to manganese ferroalloy tapping and included a substantial study on slag properties. Metal

and slag were treated as a mixture and thus a total tapping rate was calculated, not the individual tapping rates of slag and metal. They applied the Kozeny–Carman expression, typically applied in laminar flow, to account for the pressure drop due to the particle bed:

$$\Delta P = \frac{180\mu(1-\varepsilon)^2}{\Phi^2 d_p^2 \varepsilon^3} v_t r_t \quad [3]$$

where μ is liquid viscosity, v_t is tapping velocity, r_t is tap-hole radius, ε is particle bed porosity, d_p is particle diameter and Φ is particle sphericity. The particle bed resistance is, therefore, accounted for in a similar manner as for a porous material. Olsen and Reynolds^[28] also focused on tapping of manganese alloys and published a model for slag and metal tapping where slag and metal were treated as separate phases providing individual tapping rates for these immiscible phases. The Ergun equation, which is applicable to turbulent flow, was used for calculating the pressure drop due to the particle bed:

$$\Delta P = \frac{150\mu(1-\varepsilon)^2}{\Phi^2 d_p^2 \varepsilon^3} v_t r_t + \frac{1.75\rho_m(1-\varepsilon)}{3\Phi d_p \varepsilon^3} v_t^2 r_t \quad [4]$$

The results of Olsen and Reynolds^[28] indicate that the Ergun equation is more reliable for this application than the Kozeny–Carman equation, since the Reynolds number in the tapping process indicates turbulent flow. Results obtained using the Ergun equation were superior to those obtained with the Kozeny–Carman equation when comparing with the experiments of Vango *et al.*^[23]

Table I summarizes the work done in reduced order modeling of tapping flow.

B. CFD Modeling

Computational fluid dynamics (CFD) is the method of numerically solving the equations for conservation of mass, momentum and energy to compute fluid and heat flow.^[29] These equations are mathematically represented as follows^[30]:

- Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad [5]$$

- Conservation of momentum

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) = -\nabla P + \nabla \cdot [\mu_{eff}(\nabla u + (\nabla u)^T)] + \rho g + S_u \quad [6]$$

- Conservation of energy

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho h u) = -\frac{DP}{Dt} + \nabla \cdot (k \nabla T) + S_h \quad [7]$$

where u and ρ are the fluid velocity and density, μ_{eff} is the effective viscosity—accounting also for turbulence, P is the pressure in the fluid, S_u is a momentum source term, h is the enthalpy, T is the temperature, k is the thermal conductivity of the fluid and S_h is a source/sink term accounting for instance for radiation. The effect of the particle bed resistance in the furnace can be included by adding the pressure drop across the bed calculated by the Kozeny–Carman equation (Eq. [3]) or the Ergun equation (Eq. [4]) as the source term S_u to Eq. [6] without affecting the simulation complexity considerably. The interface between the different fluids is often tracked using a Volume of Fluid (VOF) method. Other multiphase flow approaches, such as Euler–Euler and Euler–Lagrangian, are rarely used in tap-hole flow simulations as the interface between the immiscible fluids (metal and slag) is not traced. The Euler–Lagrangian approach, which is also called discrete element method (DEM), has however been used to study the movement of solid particles forming the porous zone.^[23]

There are several commercial and open source CFD software available in the market such as Ansys® Fluent,^[31] OpenFOAM®,^[32] FLOW-3D®,^[33] COMSOL Multiphysics®^[34] and STAR-CCM+®.^[35] Many of them are user-friendly packages with a graphical user interface (GUI), reducing the mathematical and programming complexity. On the other hand, open source software often requires more programming and mathematical skills, but can provide better control over parameters that need to be solved, as the source code is available and can be modified according to requirements.

CFD has been applied to metallurgical processes since the 1980s but the first work on metal tapping dates to 2001, when Dash *et al.*^[36] optimized the length of the tap-hole block inside the furnace to reduce the peak shear stress in the furnace hearth which occurs at the tap-hole due to high velocity of metal. The authors included the effect of porosity *via* the Kozeny–Carman formulation, *i.e.* excluding inertial effects in the porous

Table I. Overview Over Work Done and Strategies Employed in Reduced Order Modeling of Tapping

Article	Entry Losses	Channel Losses	Interface Deformation	Ferroalloy	Porous Model	Phase Model
Mitsui <i>et al.</i> ^[25]		+				single
Nouchi <i>et al.</i> ^[22]			+		Kozeny–Carman	mixed
Iida <i>et al.</i> ^[26]		+			Kozeny–Carman	mixed
Shao & Saxen ^[27]	+	+			Kozeny–Carman	immiscible
Muller <i>et al.</i> ^[9]		+		+	Kozeny–Carman	mixed
Olsen & Reynolds ^[28]	+	+	+	+	Ergun	immiscible

zone. In 2004, Dash *et al.*^[37] expanded their research and optimized the angle of tap-block to the horizontal axis to minimize the peak shear stress. Their results showed that a tap-hole block length of 0.75 m and an angle of 15 deg with the horizontal led to minimum peak stress during tapping.

The effect of the particle diameter in the packed bed on tapping rates was studied in 2005 by Nishioka *et al.*^[38] As in previous studies, the effect of the particle bed was included using the Kozeny–Carman formulation. The authors reported that the tapping flow rate increases by up to five times when doubling the diameter of the tap-hole. At a constant porosity, changing the particle size from 15 to 60 mm led to a maximum difference of 13 pct for overall tapping rate, while the maximum metal tapping rate decreased by 16 pct and slag tapping rate increased by almost 50 pct. Nishioka *et al.*^[39] further simulated the effect of other parameters such as porosity, particle diameter distribution, the presence of an impermeable zone, slag viscosity and presence of a coke free zone on the tapping rates. Changing the porosity from 0.2 to 0.5, resulted in a maximum difference of 12 pct in the overall tapping rate, while the maximum slag tapping rate increased by approximately 10 pct. The metal flow rate decreased insignificantly by these changes. The presence of a coke free zone or impermeable zone of 2.2 m height from the bottom had no effect on the tapping rates. Viscosity was found to have an strong effect on the tapping rates, increasing with 11 pct when the slag viscosity was reduced by 75 pct.

Kadkhodabeigi *et al.*^[40] studied tapping of molten silicon and found that the flow in the tap-hole is highly dependent on the conditions inside the furnace. They found an increase in tapping flow rates with increasing crater pressure in a submerged-arc furnace. This study was extended by Kadkhodabeigi *et al.*^[20] to include the influence of other parameters such as metal column height and permeability of the packed bed on the tapping flow rate, gassing and tapping time. The effect of the porous particle bed on the flow was considered using the Ergun equation (Eq. [4]). The mass flow rate was almost doubled by increasing the crater pressure from 30 to 200 mbar, while the effect of metal height was less significant as the mass flow rate increased by only 33 pct on increasing the metal column from 4.5 to 12 cm. Finally, a reduction of 60 pct in the permeability of the packed bed (only reducing particle diameter) did not lead to a significant change in the flow rates.

Shao *et al.*^[41] simulated the two-phase flow in the tap-hole of a blast furnace for a short period (10 seconds) during which the slag-iron interface falls from above to below the tap-hole. The results show tap-hole flow of iron and slag with a well-defined interface between them during the middle stages of tapping (2-5 seconds). In the beginning and the end of tapping, largely one phase dominates with a wavy interface. A developing velocity profile for iron and slag in the entrance region and fully developed flow in the rest of the tap-hole is also observed.

In 2017, Reynolds and Erwee^[42] performed an optimization of the shape of the tap-hole inlet and the launder and visualized their effect on the flow of metal and slag in the tap-hole and ladle respectively. The authors utilized large eddy simulation (LES) to better understand the turbulent effects in the tap-hole and the transition from laminar to turbulent flow. Their results showed that a rounded entrance showed delayed onset of turbulence and v-shaped launder resulted in narrower cross-section of metal falling into the ladle compared to rectangular shaped launder, reducing the chances of re-oxidation. The importance of the tap hole shape was also considered by Kirschen *et al.*^[43] aiming to optimize the design of the tap-hole in an electric arc furnace used for steel production. A conical shaped tap-hole was found to lead to a more stable flow of metal compared to standard cylindrical channel.

Reynolds *et al.*^[44] extended their work from 2017^[42] by including the presence of a particle bed and analyzed the sensitivity of material properties on tapping rates. The presence of a particle bed in either phase reduced the tapping rates of the respective phase. The particle bed parameters affected the flow rates the most, slag viscosity and metal density were also found to have a significant effect, while the effect of metal viscosity was insignificant. Varying the design parameters such as increasing tap-hole diameter led to a considerable increase in the mass flow rate of the metal and slag, while the length of the tap-hole did not contribute significantly.

Vango *et al.*^[23] in 2018 applied the VOF method to solve the flow and interface of a single liquid phase and coupled this to the discrete element method (DEM) in order to account for the particle bed. Their results were validated against their own experimental data. In 2019, the authors extended the study in Vango *et al.*^[21] and prepared a database of packed bed states consisting of the bed porosity, mass of the metal/slag and Sauter-mean diameter of the bed particles from the information of metal/slag height, weight of the burden and particle size distribution of the packed bed using the CFD-DEM coupling approach. This database was then used to obtain dynamic packed bed void fraction and solid phase configuration for simulating the flow during tapping. The effect of porosity was modelled by the Koch and Hill drag relation, which has similar properties to the Kozeny–Carman formulation.

Olsen *et al.*^[45] demonstrated coupled heat and fluid flow simulation to understand the factors affecting the temperature profile in the tap block and the surrounding region. They reported high effectiveness of water-cooled system compared to natural cooling and high temperatures in the tap block with convection (when metal is being tapped) compared to heat conduction of the refractory material (no tapping).

In addition to the above-mentioned studies on fluid drainage in the tapping process, work has also been conducted on other aspects of tapping. In 2018, Johansen *et al.*^[46] modified the tap-hole and the ladle configuration in cascade tapping of ferrochrome to reduce the loss of metal overflowing from the metal- to slag ladles. By reducing the fall height and increasing the

angle of the ladle outlet, the metal loss could be reduced by up to a factor of 30. This is consistent with experimental studies from the steel industry by Kim *et al.*^[47] and the review of Lee.^[48] Some work has also been on safety and environmental issues around the tap-hole. Metal droplets may disperse and re-oxidize during tapping, and suspend as oxides in the air leading to pollution in the working area around the furnace. This issue was addressed by Ravary *et al.*^[49] in 2010, suggesting design modifications to the tapping area with an objective of preserving the health of workers, leading to an improved ventilation of dust and process gases. In 2015, the flow patterns of the pollutants exiting from the tap-hole were studied by Ma *et al.*,^[50] utilizing CFD-DEM coupling to visualize the dispersion of suspended particles. They observed that high winds in the furnace area leads to faster reduction of the particle content in the environment and compared the effect of different wind speeds and direction.

Table II highlights the application of CFD in the pyrometallurgical field for determination of fluid and heat flow in the furnace hearth as well as in the tap-holes. Fluid flow simulation are frequently performed compared to heat flow simulation because many of the factors affecting the furnace operation are fluid flow related. It can be seen in Table II that the Ergun equation has been applied in recent work as an alternative to Kozeny–Carman, thereby allowing for inclusion of inertial effects on the flow in the packed bed. ANSYS Fluent has historically been the most commonly used simulation software, while open source CFD software such as OpenFOAM and CFDEM^[51] have received attention more recently.

C. Conceptual Model for Tapping

From the knowledge and findings given in the literature cited above, it is possible to design an outline of a conceptual model for furnace tapping. There are still details which have to be studied, but the main principles are starting to be revealed.

For drainage of slag and metal through a tap-hole, it is known from the models that the hydrostatic pressure head is the driving mechanism of drainage and therefore the molten bath level as well as gas pressure are of great importance for tapping. Pressure created from gas producing reactions vary between different ferroalloy production processes, meaning that the gas contribution is insignificant for certain ferroalloys, while for others it should not be neglected. However, the hydrostatic pressure head from slag and metal is the dominating driving force. This has been shown by several CFD studies, but it can also be seen from Eq. [1] based on Bernoulli's principle for the tapping rate. It is evident from this equation that liquid density is the most significant material property affecting the tapping process—heavy liquids will drain faster from the tap-hole than light liquids owing to gravity. Moreover, the tapping rate directly depends on the tap-hole diameter—a bigger opening will naturally promote a higher tapping rate.

For tapping of slag and metal from a furnace, we need to look beyond Bernoulli's equation in its simplest form since two immiscible liquids are present and they reside in a particle bed. The particle bed forms a resistance to the flow which reduces the tapping flow rate. The resistance is given by the particle size, particle packing (*i.e.* bed porosity), the liquid viscosity and the liquid density. It is much easier for a gas than a highly viscous slag to flow through a particle bed. The resistance increases with decreasing particle size and decreasing porosity. Studies with both CFD and reduced order models show that most of the particle bed resistance is found in the region near the tap-hole. This is explained by the acceleration of slag and metal happening in that region as it converges into a narrow tap-hole.

Since the two liquids are immiscible, they will drain with different tapping rates. Normally the lower liquid, which for most smelting processes is metal, will drain first. It will stop draining once the level goes beneath the tap-hole level. However, if the level of the metal is below the tap-hole upon the start of the tapping, metal may

Table II. Overview Over Work Done and Strategies Employed in CFD Simulations of the Tapping Process

Article	Flow		3D	Transient	Multiphase	Ferroalloy	Software	Porosity
	Fluid	Heat						
Dash <i>et al.</i> ^[36]	+		+				Phoenics	Kozeny–Carman
Dash <i>et al.</i> ^[37]	+		+				Phoenics	Kozeny–Carman
Nishoka <i>et al.</i> ^[38]	+		+	+	+			Kozeny–Carman
Nishoka <i>et al.</i> ^[39]	+		+	+	+			Kozeny–Carman
Kirschen <i>et al.</i> ^[43]	+		+	+	+		Ansys Fluent	
Kadkhodabeigi <i>et al.</i> ^[40]	+		+	+	+	+	Ansys Fluent	Ergun
Ravary <i>et al.</i> ^[49]	+		+	+		+	Ansys Fluent	
Kadkhodabeigi <i>et al.</i> ^[20]	+		+	+	+	+	Ansys Fluent	Ergun
Shao <i>et al.</i> ^[41]	+		+	+	+		Ansys Fluent	
Ma <i>et al.</i> ^[50]	+		+	+	+	+	Ansys Fluent	
Johansen <i>et al.</i> ^[46]	+		+	+		+	Ansys Fluent	
Olsen <i>et al.</i> ^[45]	+	+	+	+	+	+	Ansys Fluent	
Vango <i>et al.</i> ^[23]	+		+	+	+		CFDEM@coupling	
Reynolds <i>et al.</i> ^[44]	+			+	+	+	OpenFOAM	Ergun
Vango <i>et al.</i> ^[21]	+			+	+		OpenFOAM	Koch and Hill

not be tapped at all. The upper liquid, *i.e.* slag, will normally start draining after metal starts to drain. It should be noted that slag and metal will drain simultaneously if the interface between them is somewhat close to the height levels covered by the tap-hole. This feature is illustrated in Figure 4,^[28] where tapping rates for slag and metal in a FeMn furnace are plotted for a case with initial metal and slag levels of 30 cm each. Both slag and metal are tapped simultaneously throughout the given time interval, while their tapping rates are not equal. Metal has a higher tapping rate in the beginning of the tap, and towards the end, the metal tapping stops while slag continues to be tapped. This applies to slag and metal being tapped through a single tap-hole.

It should also be noted that the interface between slag and metal and slag and gas is not flat. Due to the drainage velocities a suction force (*i.e.* dynamic pressure) causes the interface to deform towards the tap-hole. This will cause slag to tap earlier than expected from its average level, while metal tapping will take

longer. This is illustrated in Figure 5 which is created from a CFD simulation. This will result in slag tapping occurring earlier than expected from its average level, and metal tapping will take longer.

The mechanisms mentioned here can be explained and calculated with the models cited in the preceding sub-chapters. The knowledge and techniques associated with the models can be applied to enhance tapping as discussed in the following chapter.

III. APPLICATION TO TAPPING

The application of modeling methods to real-world problems in the ferroalloy industry remains at an early stage of development. As is clear from the previous sections, the majority of work in this field has so far been focused in two main areas. The first is specific design verification or modification, in which a physical or numerical model of an individual component of the tapping system is constructed after it has been designed using more traditional engineering methods. The second is broad fundamental studies of various aspects and phenomena in generic tapping systems, in which the parameter spaces of simplified models are explored in order to build deeper understanding of the tapping process in general.

While these approaches have been largely successful to date, the potential inherent in modeling of tapping processes is considerably wider in scope. With the advent of the fourth industrial revolution (4IR) modeling methods constitute a powerful toolbox that can be leveraged by high-level software automation for design, optimization, and control purposes. This can take several forms:

- Virtual prototyping, in which numerous variations of equipment and process designs are tested extensively using computer models as front-line engineering tools, in order to arrive at an optimized final design,
- Digital twinning, in which predictive numerical or computational models are integrated with live data from furnace plants in order to provide model-based control, operator guidance, and early warning systems,
- Inverse modeling and soft sensors, in which models are used to infer and interpolate between real measurements (such as those obtained from furnace feed and electrical systems, thermocouples, sidewall cooling elements, *etc.*) in order to provide virtual sensors which can be used by plant control systems as though they were real instruments,
- Industrial Internet of Things (IIoT) applications, in which knowledge obtained from modeling (or even simple models themselves) are directly integrated into instruments and support equipment installed on the tapping system, facilitating the development of more distributed and self-organizing control strategies,
- Data-driven modeling, in which large quantities of measured tapping data for a particular furnace operation are analyzed using data science and ma-

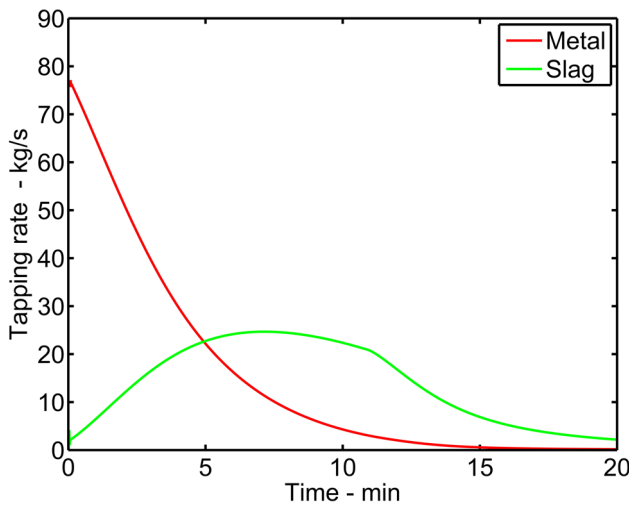


Fig. 4—Tapping rates for slag and metal in a FeMn furnace as a function of time.^[28]

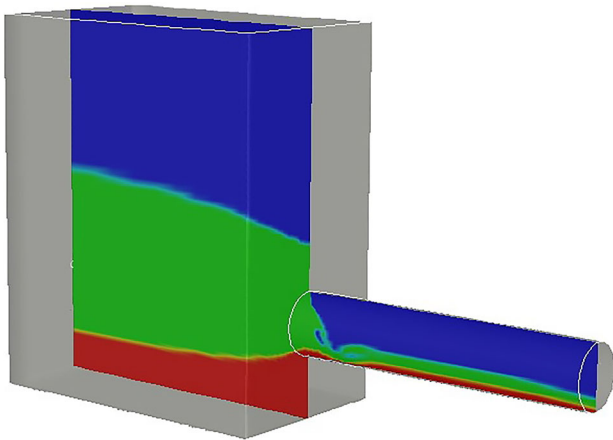


Fig. 5—Example of slag (green) and metal (red) phases during tapping from a FeMn furnace. The tap-hole diameter is 10 cm. (Color figure online).

chine learning tools in order to support and augment more traditional empirical or fundamental modeling.

The utility of virtual prototyping has already been demonstrated in the HSE field for the development of new equipment and operational procedures for managing gas and dust emissions during ferroalloy tapping.^[49,52] Advanced models of other parts of furnace tapping systems are potentially able to predict a wide range of phenomena relevant in HSE applications including tap-hole wear and damage, splashing and accidental overflows from tapping runners and ladles, thermal radiation loads from molten metal and slag surfaces, outcomes of different equipment failure modes, and so forth. In the more general virtual prototyping space it is expected that computational modeling of ferroalloy furnace tapping systems will be able to provide tangible economic benefits by suggesting design optimizations that improve phase separation efficiencies, increase robustness and tolerance to tapping variability, and reduce maintenance and consumables.

Digital twinning is expected to evolve naturally from developments in virtual prototyping as models become more sophisticated and available computational power advances. It is expected that while virtual prototyping focuses on the detailed design of individual components of the furnace tapping system, digital twin models will unify component models into a single framework in order to account for interaction effects. An example of this is shown in Figure 6, in which information from various sub-models carries through a simple flowsheet for a ferroalloy furnace tapping system. The availability of powerful software integration and automation tools

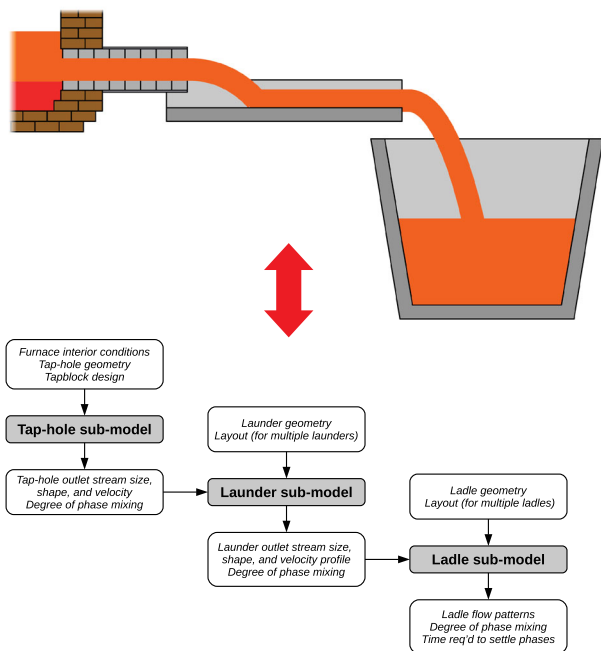


Fig. 6—Furnace tapping system (top) with corresponding integrated modeling flowsheet (bottom).

in high-level general purpose languages like Python is expected to be a key driver of digital twin development in the future.

The use of inverse modeling and soft sensors to expand measurements from instrumentation is already quite commonplace in blast furnace operations for hearth and sidewall integrity monitoring.^[53,54] It is anticipated that extension of such techniques to furnace tapping systems will give plant operators a clearer picture of the interior condition of tap-holes and tapblock lining assemblies in particular, facilitating efficient just-in-time maintenance practices and averting catastrophic failures.

IIoT applications^[55] are still in their infancy in the ferroalloy industry. However, it is expected that with ongoing advances of instruments and sensors, modeling technologies from virtual prototyping and digital twinning will trickle down to this level in due course. A network of smart instrumentation and equipment will be capable of not only communicating and sharing information with each other, but also running simulations to enhance their knowledge of the tapping system and improve their actions. Automation and control of tapping systems are therefore likely to become considerably more distributed in such environments, requiring only supervisory monitoring and high-level objectives to be provided by plant operators.

Data-driven modeling is expected to see greatly increased application in the control and management of furnace tapping systems in the future. The enabling technologies of data science and machine learning are already seeing significant adoption in other areas of pyrometallurgy such as quality monitoring and control.^[56] By combining the top-down approach of data science methods with bottom-up models based on process fundamentals, powerful augmented modeling frameworks can be conceived which are fitted optimally to large dynamic real-world datasets while remaining flexible enough to extrapolate realistically beyond the bounds of that data. Together with IIoT, such techniques are also expected to feed back into the development of more advanced modeling methods for virtual prototyping and digital twinning, closing the loop of new applications for modeling in furnace tapping systems.

IV. CONCLUSIONS AND OUTLOOK

Tapping is a ubiquitous and cross-cutting furnace operation in the ferroalloy industry, and poses a number of challenges ranging from the complexity of the physics involved to the extreme hazards faced by the personnel who work on it. It would, therefore, seem to be an ideal subject for the application of modeling techniques, which are able to build scientific and engineering knowledge of a process *via* physical or numerical proxies. However, it is clear from the present review that research and development in the field of ferroalloy furnace tapping remains at a relatively nascent stage.

Arguably, the most progress to date has happened in the area of reduced-order models, with refinements and advances in the state of the art contributed by many different authors over a number of years. Such models are robust and simple, and may be easily fitted to process data from a particular operation in order to develop tailored solutions. They also lend themselves naturally to new applications in software automation and control.

Applications in physical modeling have been somewhat limited in recent times, despite the fact that this can add significant value to other types of modeling work; very little industrial data on furnace tapping are available in the open literature, and as such physical experiments are frequently the only accessible datasets against which to test and validate numerical models.

Computational modeling methods have great potential and are seeing rapid growth in both research and engineering environments. The high level of multi-physics coupling in the tapping problem together with limited data for parameters and validation means that they are primarily useful in gaining an understanding of general trends and phenomena rather than performing detailed equipment and process design at this time—but this area of tapping modeling will evolve rapidly in the future. Although we already have obtained good insight from CFD studies, more information about the conditions inside the furnace can be obtained when simulations are linked to new and better knowledge. Most modeling studies assume uniform conditions in the particle bed, while in reality the particle bed is non-uniform with varying particle size, cracks and impermeable zones. If CFD can include such defects into the simulations, we might be able to explain inconsistency between taps. This will, however, require a deeper knowledge of the furnace internal conditions, which can be gathered from furnace excavations,^[10,57] but more details are needed, especially on the conditions near the tap-hole.

It is anticipated that the adoption of methods and technologies from 4IR (including virtual prototyping and digital experimentation, digital twinning, the Internet of Things and data science) will be a strong driver for modeling of ferroalloy tapping processes. These applications are already gaining acceptance in many other parts of pyrometallurgical furnace operations, and they offer a unique opportunity to repurpose many traditional modeling methods in new and interesting ways.

Finally, it is important to appreciate that many similarities exist between tapping operations for different types of furnaces and commodities, and this should be explored further in order to build better knowledge, models, and toolsets with reduced effort and cost. modeling research from the iron and steel industry has already been used extensively in many aspects of ferroalloy smelting, and tapping is no exception. Going forward, building on such synergies to expand the capabilities and applications of modeling methods in ferroalloy furnace tapping is likely to continue to the benefit of all parties.

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